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Microthruster Propulsion for the Space Technology 7 (ST7) Technology Demonstration Mission

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For future applications to precision formation flying missions, NASA's New Millennium Program is scheduled to test colloid micro-Newton thrusters (CMNTs) on the ST7 technology demonstration mission. These CMNTs are part of a disturbance reduction system (DRS) on the ESA SMART-2 Spacecraft or LISA Pathfinder. The goal of the ST7 DRS is to demonstrate technologies necessary to meet the nanometer precision positioning control requirements of the LISA mission. In order to achieve these goals, the CMNTs are required to demonstrate a thrust resolution of less than 0.1 μN and a thrust noise of less than 0.1 μN/√Hz for thrust levels between 5 and 30 μN. Developed by Busek Co. with support from JPL in testing and design, the CMNT has been developed over the last four years into a flight-ready microthrust system. The development, validation testing, and flight unit production of the CMNTs are described. Development tests and analysis include preliminary wear tests, propellant loading process verification, flow testing, and performance verification. Validation and flight unit verification includes thermal and structural analysis, life testing, thermal and dynamic load testing, and performance verification. Final delivery of the units is planned in 2007 with and planned launch and flight demonstration 2009.

I. Introduction

Recent interest in high resolution space interferometers, such as the Laser Interferometer Space Antenna (LISA), that require precise position control has created an interest for developing precise low thrust thruster technology. The primary objective of the Laser Interferometer Space Antenna (LISA) is to detect and measure as yet unobserved gravitational waves produced by compact binary systems and mergers of super massive black holes‡. Only interplanetary space can provide the relative disturbance free environment suitable for these long time scale (1-10,000 s) measurements that could lead us to a better understanding of the beginning and current state of the universe. Yet, even interplanetary space is subject to minute disturbances, such as solar wind, radiation, and photon pressure that could mask the influence of gravitational waves on free-floating proof masses. To shield the gravitational wave instrument, LISA consists of a precisely controlled set of spacecraft that follow the array proof masses within approximately 10 nm and provide a disturbance free environment. Calculations have shown that to reach the sensitivity level of interest, the disturbances to the proof masses can be no more than 3×10^{-15} m s^{-2} Hz$^{-1/2}$ in the 10^{-4}-1 Hz bandwidth.

The LISA instrument consists of six proof masses, two in each of three Gravitational Reference Sensors (GRSs) that are on all three spacecraft, and a laser Interferometry Measurement System (IMS). Detection of gravitational waves follows from measuring the time-varying strain in the length between proof masses using a Michelson-type

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‡The LISA websites, http://lisa.jpl.nasa.gov/ and http://sci.esa.int/science-e/www/area/index.cfm?fareaid=27, provide the most comprehensive information and list of technical references available for LISA. The ST7-DRS website is located at http://nmp.jpl.nasa.gov/st7/index.html.

interferometer sensitive to picometer level displacements. As shown in Figure 1, the nominal arm length (the distance between spacecraft and reference proof masses) is 5 million kilometers with the spacecraft arranged in an equilateral triangle. The triangle formation is placed into a heliocentric orbit at 1 AU, 20 degrees behind the Earth by three propulsion modules that separate from each spacecraft after insertion. The plane of the triangle is tilted 60 degrees with respect to the ecliptic to maintain a stable orbit configuration. The Disturbance Reduction System (DRS) for each spacecraft consists of position sensors in the GRS, micro Newton thrusters as actuators, and drag-free control laws that maintain the spacecraft orbits and cancel out the environmental disturbances (mainly solar photon pressure) to the spacecraft. To observe gravitational waves effectively, the LISA instrument must operate in a drag-free environment with stringent, high-resolution requirements on both the pointing and the translation of the spacecraft.

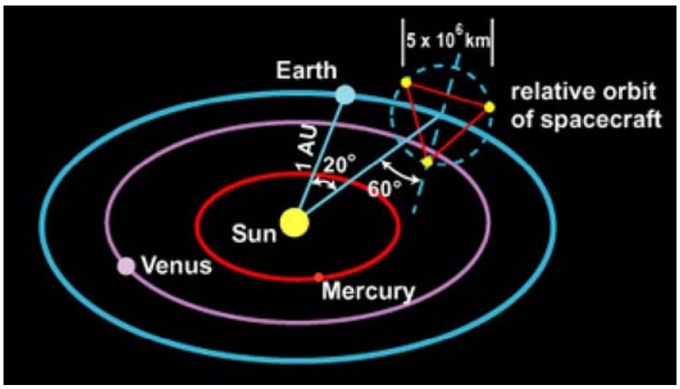

Figure 1. Orbit and spacecraft configuration for the LISA mission. The constellation rotates as it orbits the sun.

To accomplish the LISA mission and develop the technology that will make these measurements possible, the an international cooperative mission has been sponsored by the European Space Agency (ESA) and NASA. In addition, due to the unique and challenging nature of the measurements, each agency is sponsoring a technology demonstration mission prior to LISA in the near future. Space Technology 7 Disturbance Reduction System (ST7-DRS) is the US technology demonstration mission, sponsored through the NASA New Millennium Program and managed by the Jet Propulsion Laboratory (JPL). The LISA Test Package (LTP) is the European technology demonstration mission, part of the ESA LISA Program. Both technology demonstration missions will be placed on the same spacecraft as part of the LISA Pathfinder Mission, scheduled to launch in 2009. Once launched, the LISA pathfinder spacecraft will be maneuvered to a halo orbit about the Earth-Sun L1 Lagrange point for a six month mission (Figure 2).

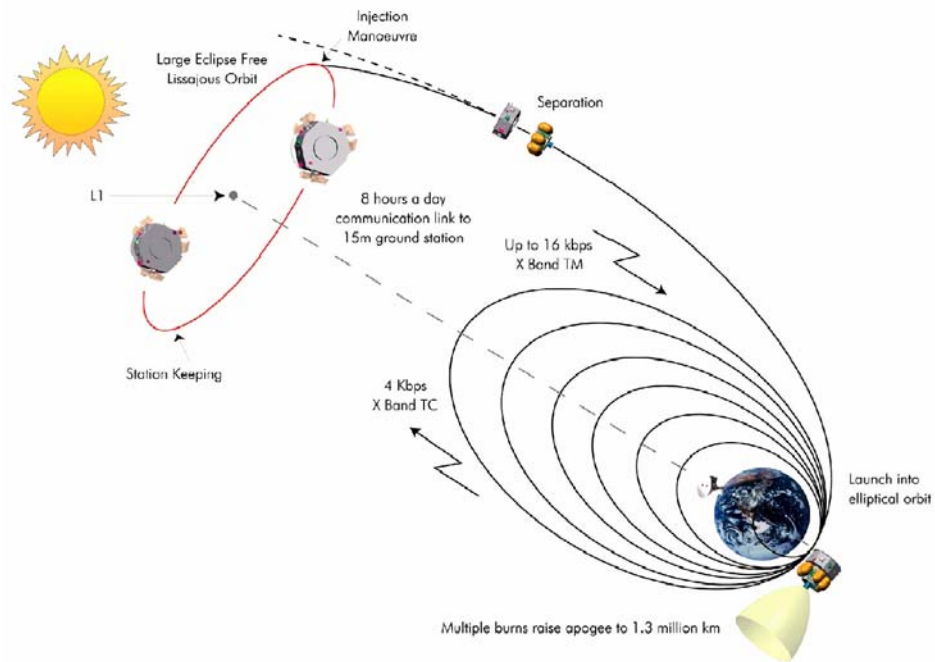

Figure 2. LISA pathfinder mission profile.

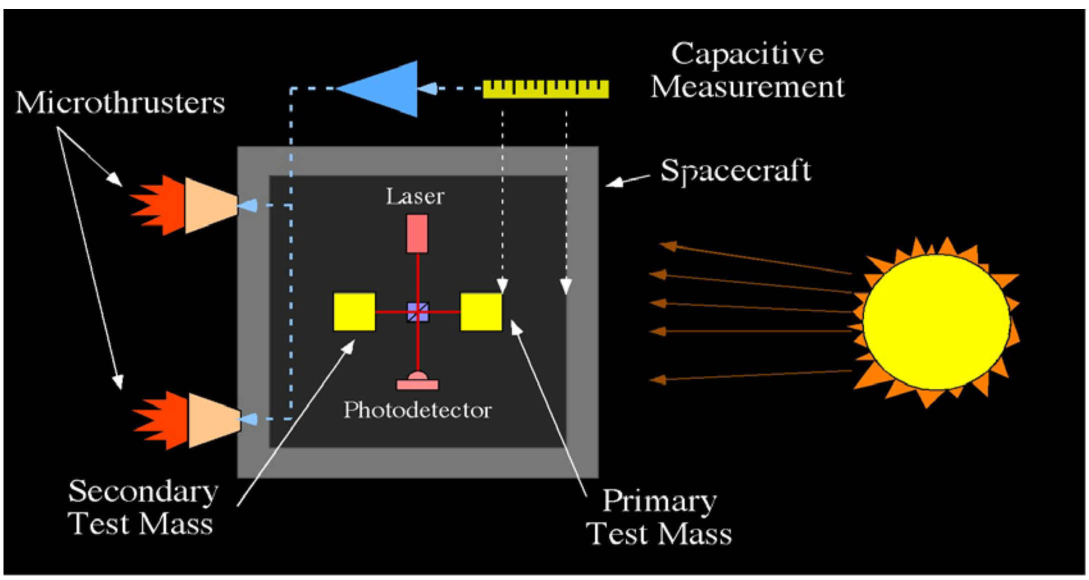

Figure 3. Disturbance reduction system concept.

The technology goals of the ST7-DRS mission are to demonstrate spacecraft position control to 10 nm/√Hz and spacecraft propulsion system thrust noise less than 0.1 μN/√Hz over a frequency range from 1 mHz to 30 mHz. These goals are accomplished by the use of two test masses (Figure 3). The primary test mass is freely floating within a spacecraft that shields the test mass from external forces. This test mass will ideally follow a trajectory determined only by the local gravitational field. Essentially flying in formation with each other, the spacecraft position must be continuously adjusted to stay centered about the primary test mass. System performance is characterized by the extent to which unwanted accelerations appear on the primary test mass and the accuracy with which the spacecraft is centered on the primary test mass.

In order to measure the level of accelerations appearing on the primary test mass, its trajectory must be compared with a reference trajectory. The reference is provided by a second identical test mass located within the same instrument assembly. Being located in the same spacecraft, the second test mass must be controlled at frequencies below the measurement bandwidth to maintain its position relative to the primary test mass, while being free of control forces within the measurement bandwidth to provide a reference for acceleration measurements. The position of the second test mass will be measured with respect to the spacecraft. To keep the second test mass as free from external disturbances as possible within the measurement bandwidth, the spacecraft attitude will be controlled to follow the motion of the second test mass in axes perpendicular to the line between the two test masses.

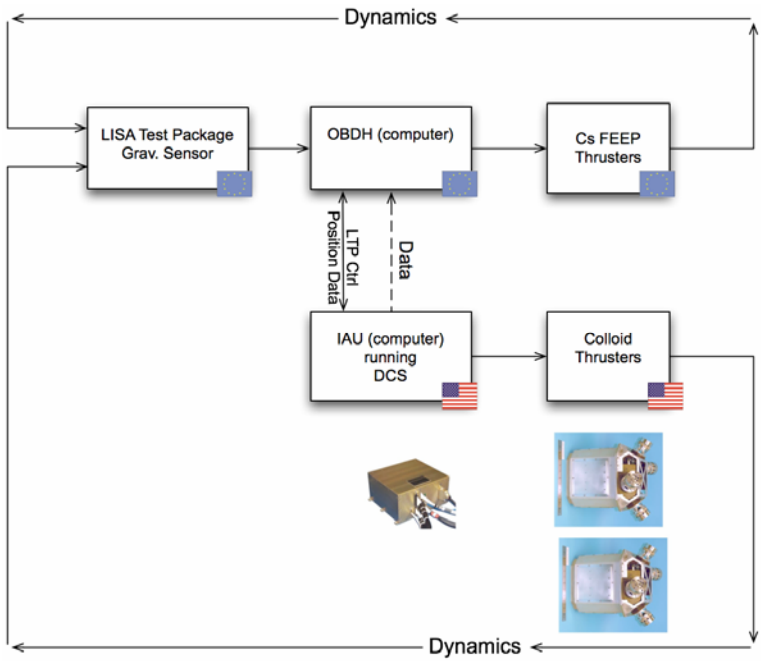

Figure 4. ST7 DRS system description.

The primary elements of the functional ST7 DRS system are shown in Figure 3. The two cubical test masses, provided by the European Space Agency, are enclosed within the cubical housings rigidly attached to the body of the spacecraft. Electrodes on the inner faces of the housings are used to measure the position and orientation of the test masses with respect to the housings. This capacitive sensing mechanism has been used in many previous missions, including the Triad drag-free demonstration and on Gravity Probe-B. A laser interferometer will measure changes in distance between the two test masses to infer the residual acceleration noise. Colloid microthrusters will be fired to oppose external forces, which are primarily due to solar radiation pressure acting on the spacecraft solar panel. The thrust will be continually adjusted to keep the spacecraft centered about the test masses. Both NASA and ESA have parallel technology development programs, including plans to develop at least two microthruster technologies. This paper describes only the US technology development effort in detail, focusing on the Busek Colloid Micro-Newton Thruster (Refs. TBD and TBD provide information on the European Field Emission Electric Propulsion (FEEP) technologies currently under consideration).

Originally, the ST7 DRS system included its own gravitational reference sensor (GRS) consisting of the test masses, capacitive sensing mechanism, and the laser interferometer. On September 12th, the DRS was descoped to eliminate the GRS. The descoped system now uses the European GRS in the LTP with the American CMNTs and Integrated Avionics Unit (IAU). The IAU, manufactured by Broad Reach Engineering, serves as the interface between the drag free sensors, thrusters, and host spacecraft. The Dynamics Control Software (DCS), delivered by Goddard Spaceflight Center, resides within the flight software executing at 10 Hz to perform the controlling functions of the DRS

II. Microthruster Requirements

To demonstrate the technology capability necessary to meet the LISA needs, the following level 1 requirements were derived for the ST7 DRS mission (Table 1). To meet these requirements, the ST7 DRS must use the LTP as its drag free sensor. The LTP sensing requirement is not a requirement on the ST7 DRS; but a requirement on the LTP for the ST7 DRS to meet its full or minimum success criteria. For the level one requirements, the position control and thrust noise requirements must be met over the 1 mHz to 30 mHz frequency range. For the period of the control life, an assessment of the operability of the thrusters will be made including delivered thrust, specific impulse, latencies, warm up times, controllability, throttleability, and accuracy. The design life for the radiation environment is 90 days.

Technology Requirement	**Full Success Criteria**	**Minimum Success Criteria**
LTP Sensing Noise	< 5 nm/√Hz	< 50 nm/√Hz
Spacecraft Position Control	< 10 nm/√Hz	< 100 nm/√Hz
Thrust Noise	< 0.1 μN/√Hz	< 0.5 μN/√Hz
Control Life	> 60 days	> 10 days

Table 1. ST7 DRS level one requirements.

Lower level propulsion performance requirements are derived from the level one requirements and analysis associated with requirements flow down. The thrust range requirement is determined by the need to counter the solar radiation pressure on the spacecraft. The thrust noise and resolution requirement are needed to meet the spacecraft position control requirement, with the upper frequency range of the thrust noise specification being extended to 5 Hz to accommodate the control loop. Thruster operational lifetime includes the 90 day mission design; but the design lifetime is 3,300 hours to accommodate a standard 50% thruster lifetime margin. The biggest difference between the LISA and ST7 requirements is obviously operational life; thus this is the most important area of technology work remaining for the LISA project after the ST7 mission.

Requirement	**ST7**	**LISA**
Thrust Range	5 to 30 μN	4 to 30 μN
Thrust Precision	< 0.1 μN	< 0.1 μN
Thrust Noise	< 0.1 μN/√Hz (5 Hz control loop)	< 0.1 μN/√Hz (5 Hz control loop)
Thrust Command Rate	10 Hz (< 0.1 s latency)	TBD
Thrust Response Time	< 100 s from max to min	TBD
Specific Impulse (30 μN point)	> 150 s	TBD
Specific Impulse (6 μN point)	> 275 s	TBD
Operational Lifetime	> 2,200 hours	> 55,000 hours
Plume Half Angle	< 35º (95% beam current)	TBD

Table 2. ST7 DRS and LISA microthrust propulsion requirements.

Environmental temperature requirements for the ST7 CMNT are shown in Table 3. Operational temperature requirements are driven by the viscosity of the propellant at the minimum temperature and the charge state of the fluid at the maximum temperature. At the minimum temperature, the increasing fluid viscosity increases the pressure differential required to maintain a constant thrust to such an extent, that the valve stroke is no longer able to increase the flow to compensate. At the maximum temperature, the ion fraction of the propellant relative to droplets increases, thereby decrease the charge to mass ratio resulting in an unacceptable thrust reduction. The minimum non operating temperature limit is driven by the potential of freezing the propellant. The maximum non operating temperature limit is driven by electronics parts limitations in the internal thruster heater. Dynamic environmental requirements are shown in Table 4.

Mode	Min (ºC)	Max (ºC)
Operating		
Design	10	30
Protoflight	-5	50
Non Operating		
Design	0	50
Protoflight	-15	70

Table 3. CMNT environmental temperature requirements at the cluster mounting flange.

Test	Axis	Frequency (Hz)	Protoflight Levels
Sine Vibe	All Axes	5 to 21 21 to 100	11 mm 0-pk 20 g
Random Vibe	In Plane	20 20 – 80 80 – 400 400 – 2000 2000 Overall	0.038 g^2/Hz + 3 dB/octave 0.15 g^2/Hz - 5 dB/octave 0.010 g^2/Hz 10.6 g_{rms}
Random Vibe	Out of Plane	20 20 – 80 80 – 400 400 – 2000 2000 Overall	0.073 g^2/Hz + 3 dB/octave 0.29 g^2/Hz - 10 dB/octave 0.0014 g^2/Hz 12.3 g_{rms}
Shock	All Axes	100 1500 10,000	20 g 1000 g 1000 g

Table 4. CMNT dynamic environmental requirements.

III. CMNT Technology Development

The Colloid Micro-Newton Thruster (CMNT) being developed at Busek Co., Inc.[1,2], includes a complete thruster subsystem: thruster head, propellant storage and feed control (microvalve), cathode neutralizer, PPU and DCIU. Thrust is adjustable from 5-30 μN by changing the beam voltage (2-10 kV) and/or propellant flow rate that determines the beam current (2.25-5.20 μA). Independent, fine control of both the beam current and beam voltage allow for precise control of thrust down to 0.1 μN resolution with <0.1 μN/√Hz thrust noise. Figure 2 shows one engineering model thruster cluster with four thruster subsystems, and Figure 9 (located at the end of the paper) shows a functional block diagram for the CMNT cluster. We will now discuss the subsystems of the Busek CMNT being developed for the ST7-DRS Mission.

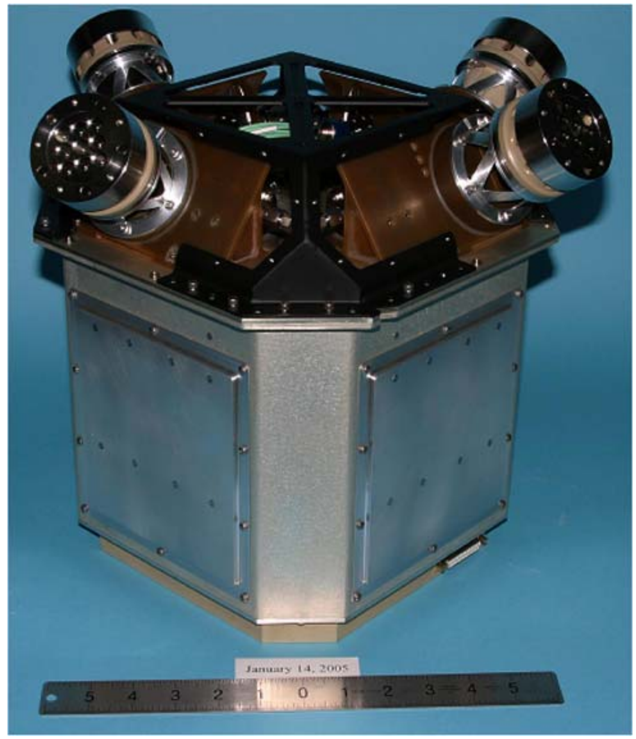

Figure 2. Engineering Model Busek Colloid Micro Newton thruster showing complete thruster (thruster head, neutralizer, PPU and propellant storage bellows unit) in a quad configuration. Taken from Ref. [1].

A. Overview of CMNT Subsystems

1. Thruster Head

The thruster head is comprised of a manifold that feeds nine emitters and the electrodes that extract and accelerate the propellant. Over the last year many design iterations have been tested including changes in electrode geometry, material, and propellant flow path through the manifold. Currently two design iterations are being tested in parallel with as much similarity between them as possible to facilitate easy integration with the rest of the subsystems.

2. Propellant Feed System

Propellant is stored in a stainless steel bellows compressed by four constant force springs set to supply the microvalve with propellant at approximately 1 atmosphere of pressure. Shown in Figure 3, the μValve is piezo-actuated using ~1 mW of power to control the propellant flow rate to better than 1 nA equivalent resolution. This level of precision corresponds to ≤0.01 μN of thrust, with a response timeover its full range of less than 0.5 s. This microvalve design has been part of multiple single- and multiple-emitter long-duration tests, accumulating over 15,0000 hours of total test time without incident.

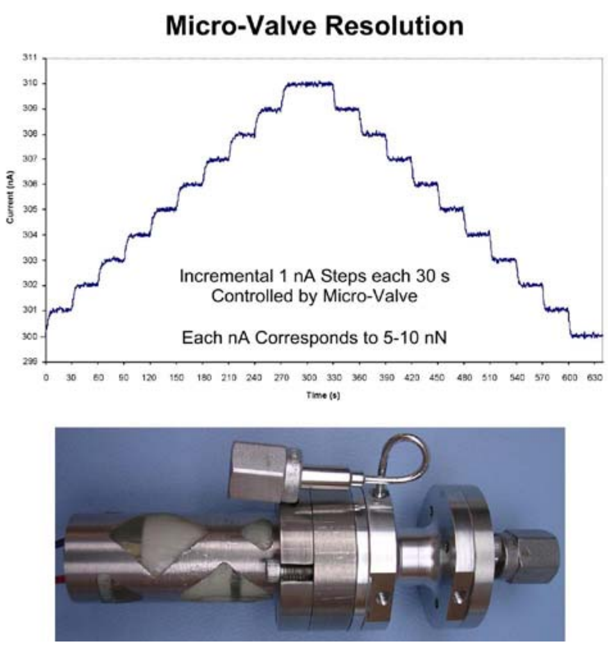

Figure 3. Busek CMNT Piezo-actuated Microvalve and graph of valve response shows < 0.1 μN resolution. Taken from Ref. [1].

3. Cathode Neutralizer

The cathode neutralizer developed by Busek is made from a carbon nanotube (CNT) base with an extractor electrode. The cathode is capable of producing 10 μA to 1 mA using extraction voltages of 250-770 V. One CNT cathode has been tested alone in an ultra-high vacuum chamber for over 13000 hours at 100 μA without incident. CNT cathodes have also been tested with thruster operating during multipl long

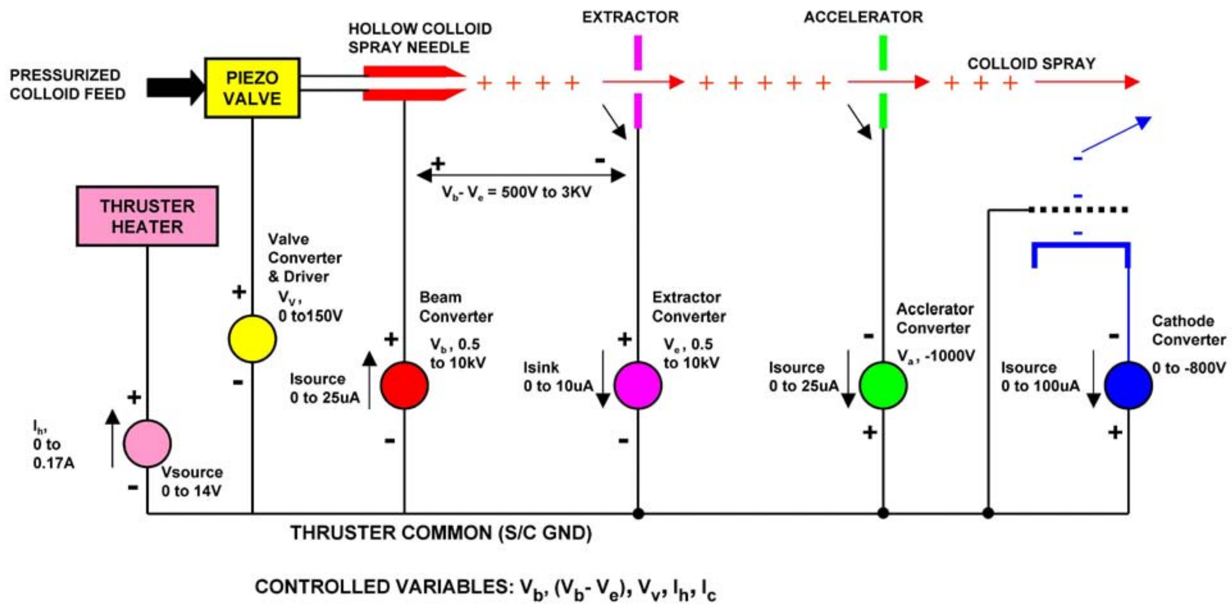

Figure 4. Thruster electrical schematic showing beam, emitter, extractor, accelerator, and cathode neutralizer voltage sources. Taken from Ref. [1].

duration tests. For ST7-DRS, only one cathode neutralizer is required per thruster cluster.

4. Thruster Electronics

The thruster electronics including 4 power processing units (PPUs) and one digital control and interface unit (DCIU) for each cluster have been developed and tested to the engineering model level. Between three sets of EM level electronics, they have now accumulated over 5,000 hours of operation under vacuum controlling complete thruster sub-systems. The PPU includes the high-voltage DC-DC converters that have been specifically designed and tested for this application by Busek Co. A schematic of the PPU and thruster interface including the thruster head, micro-valve, cathode neutralizer, and thruster heater is shown in Figure 4. Flight hardware electronics are have been fabricated, are being assembled, and the DCIU software is nearing completion.

B. Single Emitter Testing

Four long duration tests using single-emitter thruster subsystems, each exceeding 3000 hours, have been completed at Busek Co., totaling over 13,000 hours of successful operation. Each test was designed to examine the lifetime implications of changes to emitter geometry and material. The first 3000 hour test focused on emitter erosion, demonstrating that the ST7 emitters provided stable emission over the lifetime of the thruster. The second long duration test focused on emitter clogging as a lifetime limit mechanism. Together with the third and forth test, it seems clear that any clogging can be prevented by improving system cleanliness and using proper materials in the propellant flow system. The third and fourth tests also included changes to emitter and electrode geometries to improve beam current stability and reduce overspray to the electrodes.

A graph of the single emitter operating characteristics from the latest 3000 hour class test that was completed in April of 2006 is shown in Figure 5. In this test, the current was set at fixed level of 350 nA with a constant beam voltage. The current level was maintained by a closed loop control on the microvalve voltage, providing more or less propellant to the emitter as required. Due to daily and long term temperature fluctuations of the test facility, the propellant's viscosity also changed and was compensated for by changes in microvalve voltage. By normalizing the microvalve voltage data with a correlation to temperature, the effects of the temperature variation can, to a large extent, be removed, as shown by the "normalized valve voltage" trace of Figure 5. This trace shows that the microvalve voltage did not significantly shift over the duration of the test, less than 0.6 mV/hour, and that no significant clogging occurred.

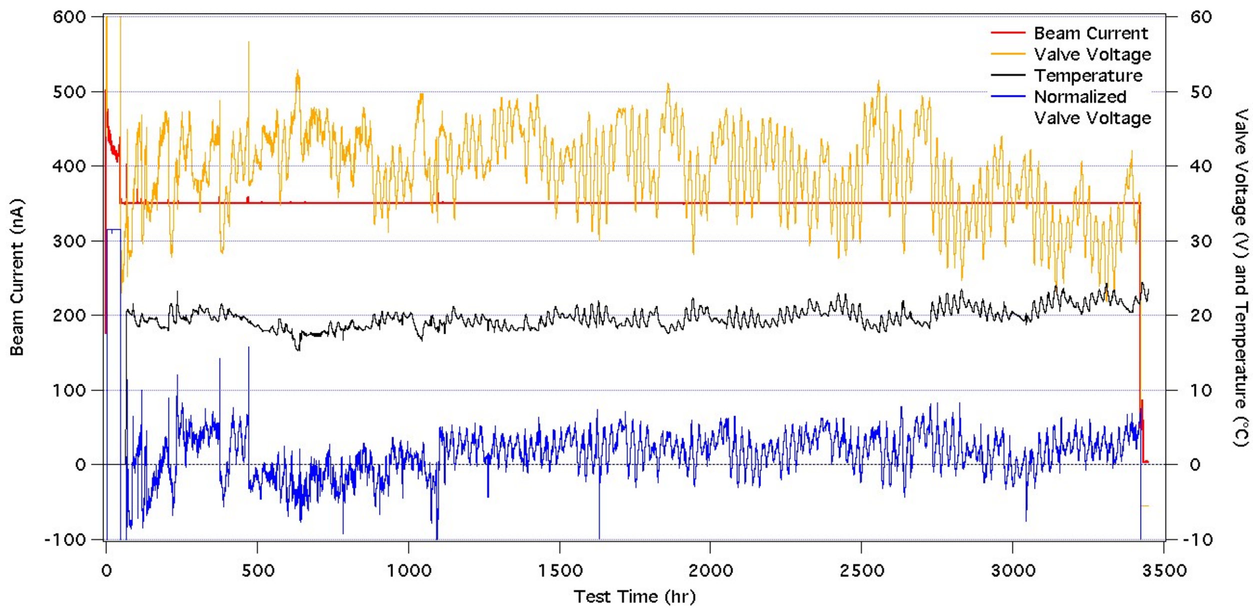

Figure 5. Operating characteristics from the 3400 hr single emitter test.

C. Multiple Emitter Testing

Starting in the Fall of 2005, focus was shifted to multiple emitter thruster head testing. However, unlike the sigle-emitter long duration tests, the multiple-emitter tests included an entire thruster subsystem with EM level hardware (including electronics). The purpose of these tests were to develop the multiple emitter thrust head design to reduce problems associated with bubbles in the propellant feed system and reduce the effects of overspray of propellant onto the extractor and accelerator electrodes.

The results from one of these tests are shown in Figure 6. From this graph, various modes of operation are shown including start-up, microvalve cycle tests, temperature control and response, the passing of bubbles by

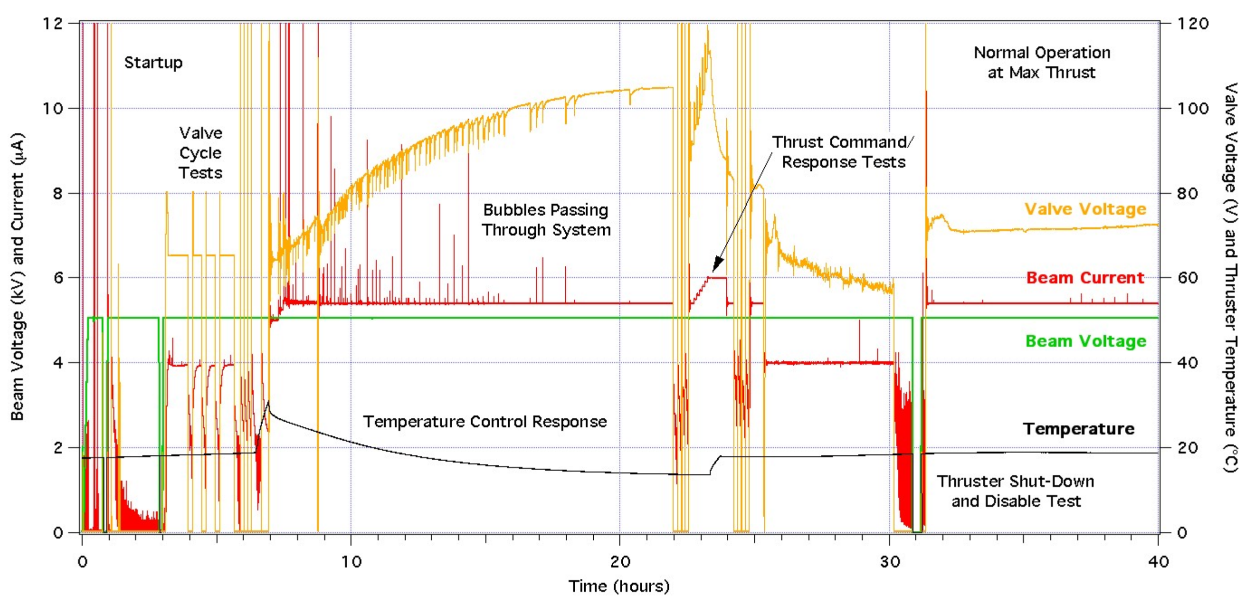

Figure 6. Operating data from developmental testing of a multiple emitter thruster head.

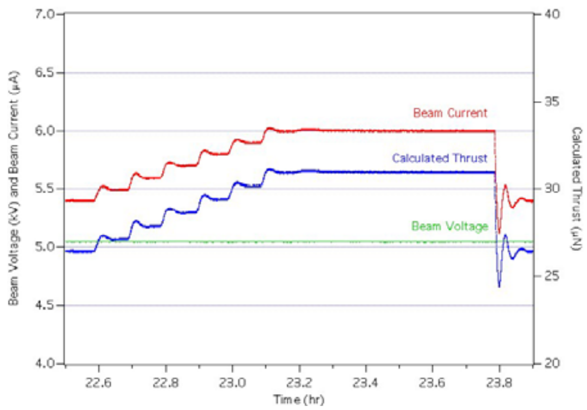

Figure 7. Response to thrust commands.

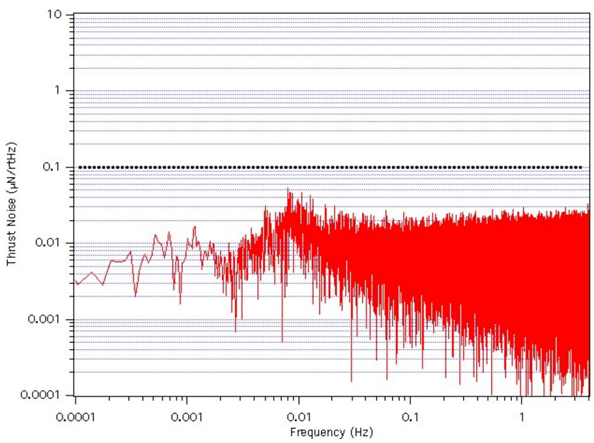

Figure 8. Thrust noise plot from hour 32-40.

operation at maximum current, thrust command and response tests, thruster shut-down, and finally normal operation.

1. *Thruster Performance*

As shown in Figure 7, the thruster responds well to thrust commands.

As shown in Figure 8, the thruster operates below the thrust noise requirement.

2. *Bubble Reduction and Elimination*

As shown in Figure 6, although bubbles are present at the beginning of the test leading to spikes in beam current, eventually the bubbles are passed out of the system.

3. *Propellant Purity*

The propellant used for the CMNT must be kept clean of any particulates and impurities including water and alcohol residues, to prevent clogging and bubble formation.

4. *Overspray Reduction*

The emitter, extractor, and accelerator electrodes have been redesigned to reduced overspray, and accommodate any that occurs.

D. Electronics Testing

Every multiple-emitter thruster head and subsystem test has included using EM-level electronics (both a PPU and DCIU) connected to and controlling the a complete thruster subsystem through a LabVIEW IAU simulator. All the electronics are operated under vacuum and in the same test facility as the thruster assembly. In this way, the operation of the thrusters through the IAU controlling the DCIU (in turn controlling the PPU) simulates more realistic operations. In fact, already a series of problems related to the DCIU, PPU, thruster interface have already been resolved.

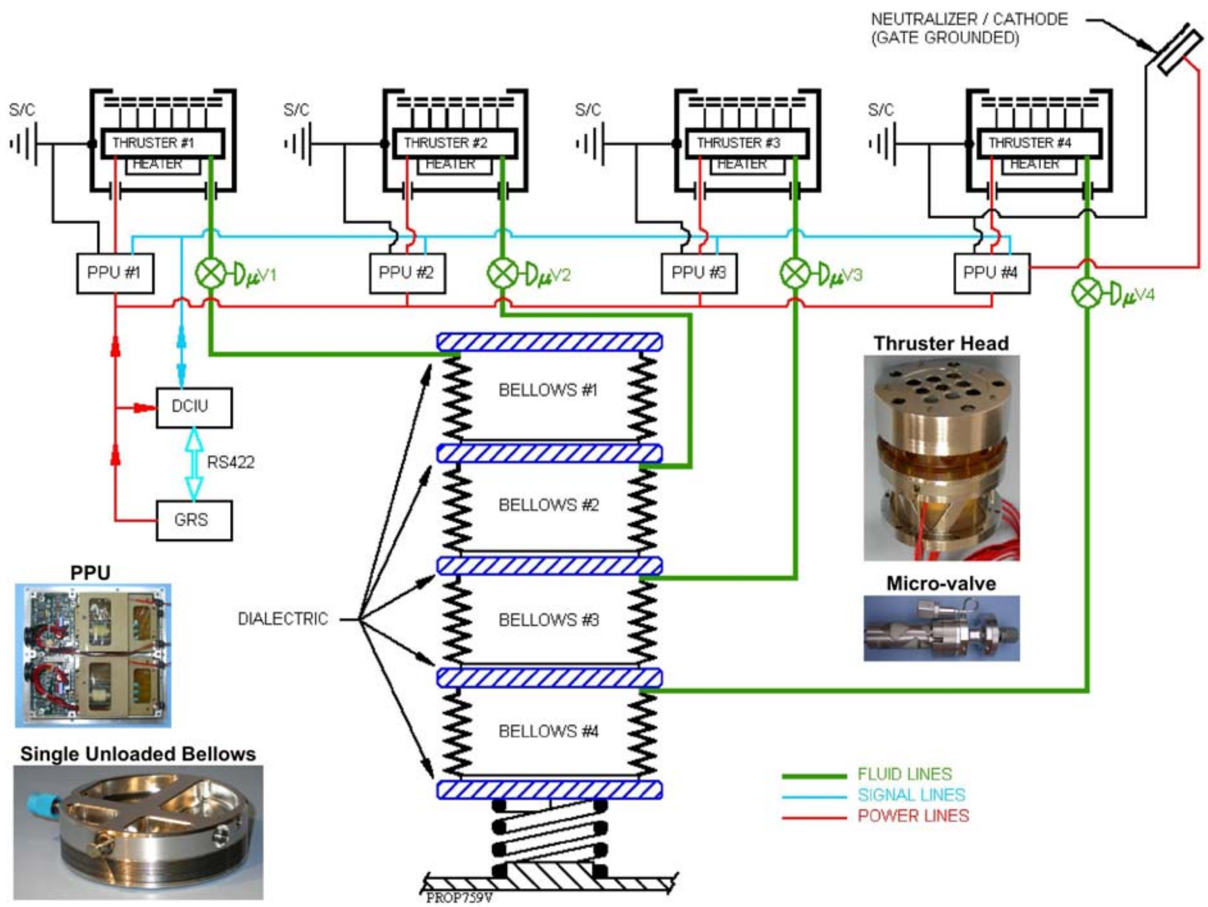

Figure 9. CMNT cluster functional block diagram with pictures of various components. Taken from Ref. [1].

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IV. Microthruster Validation Tests and Flight Production

Test validation of the Busek CMNT design for ST7 presents several challenges for a traditional qualification program. The primary challenge is the difficulty of making performance measurements with the flight clusters due to the difficulties of making thrust stand measurements with such a large mass. To avoid this problem, a validation plan was formulated to perform certain validation tests at the “box” level, with a single electronics/bellows/valve/thruster combination. Other protoflight tests are performed at the flight cluster level (Table 5). In this plan, thrust stand measurements necessary for verifying thrust range, precision, noise, response time, and specific impulse requirements are made at the box level, where the small box mass enables reasonably accurate thrust measurements. Using these box level thrust measurements, correlations can be made to enable the inference of thrust from current and voltage measurements. Current and voltage measurements are then made at the cluster level, using the model validated by thrust stand measurements, to estimate thrust at the cluster level. Because life and plume measurements are almost entirely independent of the cluster thermal and structural design, these requirements are also verified at the box level for test simplicity. Because the structural and thermal design of the box is very dissimilar to the cluster design, these requirements are validated at the cluster level by protoflight testing.

Requirement	**Box Level**	**Cluster Level**
Thrust Range	x	Partial
Thrust Precision	x	Partial
Thrust Noise	x	Partial
Thrust Response Time	x	Partial
Specific Impulse	x	
Operational Lifetime	x	
Plume Half Angle	x	
Environmental Temperature		x
Environmental Dynamics		x

Table 5. CMNT simplified validation matrix.

The first lifetime validation testing of a CMNT box was started in January of 2006. After operating for approximately 700 hours, the test was stopped due to an unrecoverable short on February 9th, 2006. Before removing from vacuum, the short was measured to form above approximately 1000 V and become open below approximately 500 V. This “partial” short had a finite (0.1 to 1 GΩ) but not constant impedance which indicated a non-permanent propellant bridge between the emitter and extractor. Testing at atmosphere isolated the short to the thruster and not the electronics or support equipment.

Optical observations of the thruster head during disassembly showed that emitter 9 was the location of the bridge. This bridge consisted of “burnt” propellant residue with a cone-shaped appearance on both the emitter spool and extractor parts (Figure 5). The other emitters did not show any sign of a propellant bridge, although some did have excess and burnt propellant residues.

Two primary differences were identified with emitter 9 and the other 8 emitters that were attributed to the short. The first difference was that the gap between the emitter spool and extractor piece was much smaller than the other needles; but still within the large predicted tolerance stack up variation. Second, emitter 9 had glue used for a collet tightening screw repair procedure. Both of these factors contributed to a small gap between the electrodes that facilitated the short. Additionally the repair glue provides and insulating layer that can allow propellant on the surface to charge up thereby also facilitating the short.

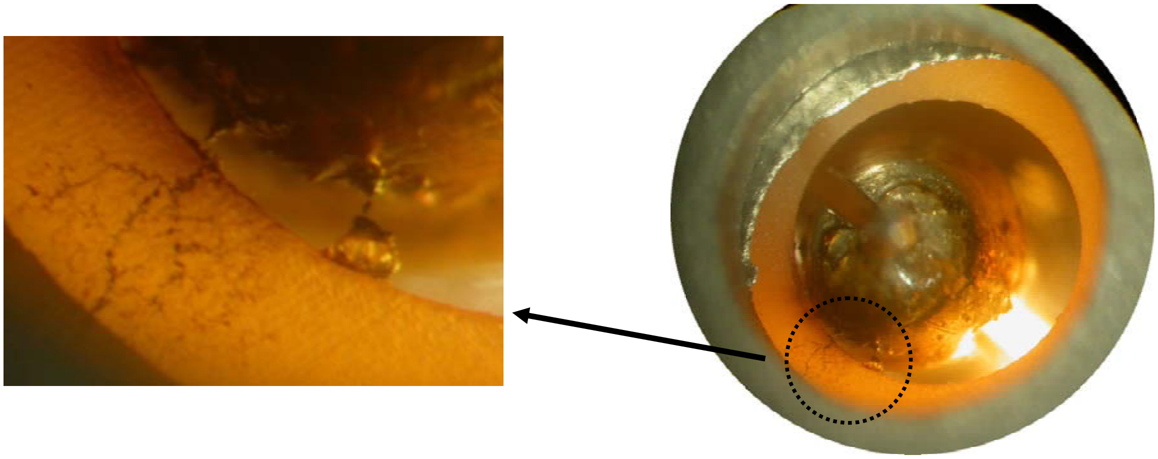

Figure 5. Life test 1 thruster short.

Several corrective actions were incorporated into the thruster design on the basis of this failure investigation. First, the collet design was changed to include a sheath over the spool to eliminate tightening screw repair issues and to increase the gap between the emitter spool and the extractor piece. Second, the assembly procedure was modified to better enable verification of a proper emitter spool extractor piece gap before final assembly. These corrective actions have been implemented on two additional life test units that are currently under test. The first unit has over 1000 hours of operation while the second unit, with an alternate needle design, has over 300 hours of operation.

Additional validation testing at the box level is primarily focused on performance testing on a thrust stand. Testing of this kind has been performed on development units; but never on a flight like unit (Reference). Preparations for thrust stand testing of a flight like thruster box are currently underway with the first preliminary results anticipated in July 2006. Final flight system integration of the thruster heads and feed system will not be performed until preliminary thrust stand measurements are obtained to insure that no major technical issues are outstanding. Final thrust stand measurements are planned for completion in August 2006. The best available microthrust measurement test bed is only capable of measuring thrust noise < 0.1 μN/√Hz at and above 7 mHz. Below this value, validated thrust models will be used to demonstrate meeting the thrust noise requirement for ST7-DRS.

Production of flight hardware is already well underway with most of the piece parts fabrication already completed (Figure 6). The flight PPU and DCIU fabrication is nearly finished with the completion of box level testing planned in August of 2006. Fabrication of the flight bellows is already complete and four are already filled with their flight propellant loads with the completion of the remaining four bellows loads planned for the end of June 2006. Microvalve piece part fabrication is complete with integration into the flow system planned for July 2006. Thruster head piece part fabrication is nearly complete with final assembly planned in July and August of 2006. Cluster structure piece part fabrication is complete with final cluster integration planned for August of 2006.

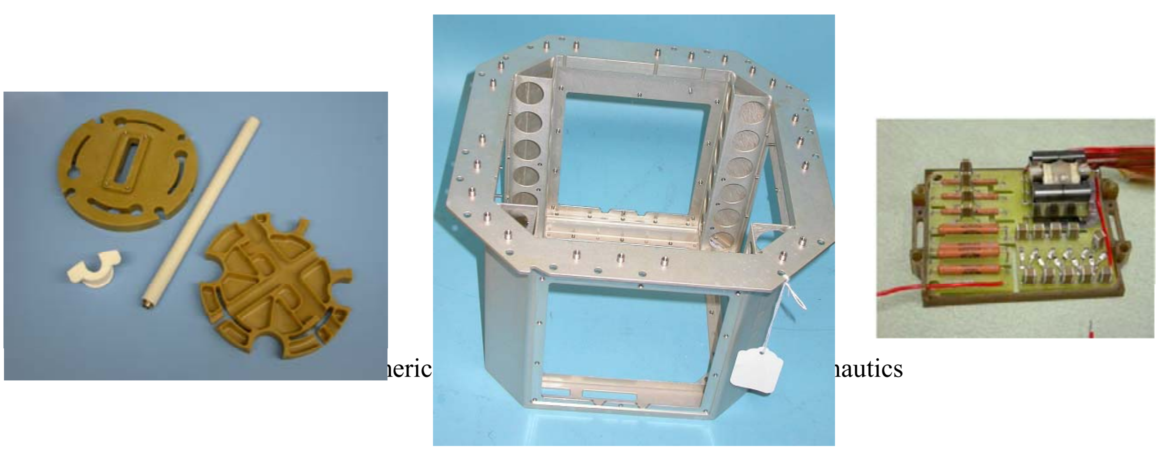

Figure 6. CMNT flight hardware.

Protoflight testing at the cluster level begins in August of 2006. Initial firing tests, to verify thrust requirements extrapolated from current and voltage measurements, will be made at Busek in August of 2006. These firing tests will be followed by cluster level dynamic environment test at NTS in August and September of 2006. The thruster clusters will then be returned to Busek for post vibration functional testing followed by thermal vacuum testing in September and October of 2006. Thermal balance testing of the thruster cluster will be differed until integration with the LISA Pathfinder spacecraft.

V. Conclusions

With developmental testing complete, the ST7 CMNT validation testing and flight production is well underway. Substantial progress has been made in colloid propellant handling, multi needle thruster operation, and colloid thruster/electronics integrated operation. Propellant cleanliness testing has resulted in the implementation of procedures that have reduced the impurity levels of problematic bubble forming moisture levels by an order of magnitude. Design features in the flow system have been implemented to mitigate bubble formation present in the current multi needle thruster. Electrode design changes substantially reduced problems associated with propellant overspray. Box level performance and lifetime validation testing is well underway with completion planned in the next few months. Final integration and protoflight testing of the two flight clusters should be completed in the fall of 2006.

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